Test Methods for Composite Structures for Pulsed Power Rotating Machines

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Abstract

Composites are an enabling technology for achieving high power and energy densities in pulsed power rotating machinery. Due to extreme thermomechanical loads, an optimized combination of structural, thermal, and electrical properties is required to achieve the desired durability and service life performance. Coupon level tests are performed to generate the results necessary to quantify these properties and guide the development of a correctly balanced composite. This paper presents a top-level discussion of test methodologies and their use that are important for evaluation of composite laminate properties for pulsed power applications. Test methodologies include: (1) hydroburst for hoop (circumferential) properties; (2) transverse tensile and shear tests for resin dominated loading; (3) radial precompression testing for viscoelastic effects; (4) fiber digestion for fiber volume and void content determination, digital photomicrographs for visual evaluation; and (5) transverse electrical conductivity tests. Both the hydroburst and transverse tensile test fixtures feature elevated temperature test capabilities. These test techniques, which are currently in use at The University of Texas at Austin Center for Electromechanics (UT-CEM), are described and typical test-generated data is discussed.

Introduction

Composite properties can be ideally exploited by high performance pulsed power rotating machinery. Carbon fiber composites have higher specific strengths than steels and other conventional materials, which allows for higher tip speeds for a given geometry. Given this, the potential exists for greater stored energy and higher power densities in smaller volumes, desirable goals for pulsed power rotating machinery. Increasing the service operating temperature of the composite through selection of resins with elevated glass transition temperatures reduces or possibly eliminates the need for active cooling, simplifying the machine design. Composite properties are anisotropic and can vary greatly with temperature. The University of Texas at Austin Center for Electromechanics (UT-CEM) uses both standard and non-standard tests to quantify composite material performance and establish design allowables.

Test Methods

Hydroburst test – An economic, reliable method to determine hoop properties is the hydroburst test, in which hydrostatic pressure is used to develop hoop stress in a test ring. Pressure acts indirectly on the ring through an oil seal. Test rings measuring 0.5 in. wide are cut from a 20 in. diameter composite cylinder. As shown in Fig. 1, the test ring and seal are captured between upper and lower platens that are preloaded together hydraulically in a press station (Fig. 2). A second hydraulic circuit pressurizes against the seal, generating radial pressure and developing hoop stress in the part sufficient to cause failure. In its current configuration the fixture can develop 6,000 psi radial pressure. Typically, the rings are instrumented with strain gauges in the hoop and transverse directions Fig. 3). Strains, radial pressure and ring dimensions are used to calculate ultimate strength and tensile modulus. This simple equation is used to calculate ultimate strength:

$$\sigma = \frac{Pd}{2t} \qquad (1)$$

where
$P =$ radial pressure
$D =$ ring inner diameter (strain compensated for growth)
$t =$ ring thickness

Tensile modulus is calculated from eq. (1) and measured strain, using this relationship:

$$\sigma = E\varepsilon \qquad (2)$$

where
$E =$ tensile modulus
$\varepsilon =$ strain

Band heaters can be installed on the hydroburst test fixture to configure it for elevated temperature operation, with capability up to ~350ºF (177ºC). This temperature is limited by the working fluid of the fixture; higher operating temperature working fluids can be used (e.g., peanut oil). Typical hydroburst results are shown in Table 1 and Fig. 4.

The hydroburst fixture can also be used for tension-tension fatigue testing. In this configuration, a control valve is added to the secondary (hydrostatic) hydraulic circuit to allow the secondary actuator (piston) to oscillate, thus creating a varying pressure range.

***Transverse tensile tests* -** Due to the direction dependent properties of composites specific tests must be performed to quantify transverse (resin) dominated properties. ASTM standard D 5450 [1] describes a transverse test method that uses complete 4 in. diameter, hoop wound cylinders that are bonded to a fixture for testing. UT-CEM altered this method slightly to allow a large number of tests to be performed economically. Test samples are cut from 20 in. diameter composite cylinders with a wall thickness of approximately 0.1 in. (Fig. 5). The samples are in a shape referred to as "dog-bone": 5 in. long, 0.5 in. wide in the test section, and 1 in. wide at the grips. Special tooling is used to cut a 3 in. radius in the sides of the test section. Tensile test grips were built to accommodate the radius of curvature of the test samples. The grips have 1 in.-14 male threads and mount to most tensile test machines.

Flat coupon transverse tensile tests are also performed according to ASTM standard D 3039 [2], with two exceptions. The gauge section is dog-boned and is intended to reduce stress concentrations and promote failure at the minimum cross-sectional area of the gauge section. The dog-bone also eliminates the need for tabbing the ends. The flat coupon sample has a length of 10 in. but the same width and dog-bone gauge section geometry as the hydroburst transverse test sample. Through the use of an environmental chamber, tests can be performed at an elevated temperature; this configuration is shown in Fig. 6 and typical results are presented in Fig. 7.

***Shear Testing* –** Some composite structures developed at UT-CEM that are filament-wound tubular laminates comprised mainly of circumferentially-directed carbon fibers. Since these structures possess rotational symmetry, the only shear stress that they can experience under (static) spin loading is R-Z shear. Unfortunately, this is a type of shear to which these structures are particularly vulnerable because the relatively weak resin layers between the carbon fiber laminae present natural shearing planes. Historically, R-Z shear stresses have not been a problem in these structures, even at very high rotational speeds (50,000 rpm), because their geometries have tended to be relatively simple.

Information about design allowable values for shear stress, especially over a range of fiber-resin systems, is rather limited. Moreover, UT-CEM has begun fabricating shapes which are more complex geometrically, such as structural arbors. In these structures, the carbon fibers may no longer be predominantly circumferentially oriented, and thus the shear stresses may be significantly higher. For these reasons, shear testing of all candidate fiber-resin systems has assumed great importance at UT-CEM.

All shear tests to date have involved tensile loading of flat coupon specimens in which two transverse notches were machined halfway through the thickness of the specimens on opposing faces (Fig. 8). These tests were performed in accordance with ASTM standard D3846-94 [3], with the exception that the standard prescribes a compressive rather than tensile loading. (Although it is expected that the interlaminar shear strength should be the same whether in tension or compression, future tests may be performed to corroborate this.) The specimens were lightly sandwiched between two guide plates to prevent out-of-plane deformations (Fig. 9). Continuous real-time measurements were made of both force and displacement during the tests. Typical data from one of these tests is shown in Fig. 10. The ultimate shear strength of the specimen is calculated by taking the load at which the specimen failed and dividing by the shear area (i.e., width of the specimen multiplied by the distance between the two notches). There is one shortcoming in these double-notch shear strength tests; it is not possible to instrument the specimens, so no strain or modulus information can be obtained.

Viscoelasticity **-** To achieve the high performance levels demanded for pulse power applications, thorough understanding of the long-term behavior of composite structural components is needed. Of particular importance is viscoelastic flow, which can limit performance life of the rotating device by loss of radial pre-compression. Radial precompression ensures that the relatively weak interfacial bond between composite laminates remains compressed even under the high centrifugal loads at operational speeds. Relaxation of the precompression, if not accounted for, degrades machine performance leading to interfacial debonding and machine imbalance.

UT-CEM uses the a fixture (Fig. 11) to address the time dependent, thermomechanical behavior of the composite. Specifically, the test method measures preload loss of composite rings due to viscoelastic flow by simultaneously imposing both radial and hoop loading in on the test specimen, which is similar to the actual loading in the rotating machine.

As shown in the Fig. 11, a composite structure is press-fit onto a thick steel cylinder. The press fit geometry is tailored to develop a specific radial compression at assembly. The assembly is then placed in an oven at some elevated temperature for an extended period of time. Strain gauges on the bore of the steel are monitored and the elastic nature of the steel cylinder is used to infer changes in preload at the composite ring interface as a function of time and temperature. The sampled preload loss data (collected over time) is then plotted in a log format, as shown in Fig. 12. Straight-line extrapolations can then be used to predict preload loss over the life of the machine for design purposes.

***Transverse electrical conductivity* -** In high current, high field generator applications, eddy currents can be generated creating losses and heat. In the case of a composite laminate made of conductive fibers (e.g., carbon fiber), transverse electrical conductivity is an important parameter to measure. A fixture was designed and built to allow for accurate and repeatable transverse conductivity measurements. As Fig. 13 shows, a section of a hydroburst ring is clamped between two conductor plates in the test fixture. In most cases, samples are painted at the electrical interface with silver paint to reduce the voltage drop between the sample and copper conductors. The fixture is installed in a typical machinist's vise, which provides the clamping force. The sample is placed in series with a capacitor bank. When the capacitor bank is discharged, voltage and current are recorded using a voltage probe and a Pearson current transformer. Using these values and the measured dimensions of the sample, the conductivity of the sample can be calculated. The clamping fixture has a pressure transducer in line such that a known clamping pressure can be applied. The clamp also has Belleville disc springs installed in both the axial and radial directions to allow for any expansion the sample may go through during the test. The exploded view (Fig. 14) shows the buckling restraint clamp to prevent any buckling that may occur due to the thermal expansion. The fixture was calibrated with a material with a well-defined conductivity.

Tests performed with the fixture have yielded repeatable results. Fig. 15 reports a typical current and voltage trace from one of the tests; Fig. 16 and Table 2 show tabulated results, based this formula:

$$\sigma = \frac{I\,l}{VA} \tag{3}$$

where
s = conductivity (W/m)
I = current (A)
l = length (m)
V = voltage (V)
A = area (m^2)

To date, however, acceptable correlation between electrical and composite properties that drive electrical properties (e.g., fiber volume) has not been well established. Particularly, the expectation that transverse electrical conductivity should increase as fiber volume increases is not borne out consistently by the data. Further development of the fixture and additional data collection is necessary to increase understanding of the mechanisms that affect transverse electrical conductivity.

***Acid digestion and Photomicrographs* -** This process is used to obtain the fiber volume of a composite laminate. In addition to fiber volume, resin content and void content are also determined by fiber digestion. A sample of the composite part is placed into a pressure vessel, covered with an acid and digested at elevated temperature and pressure to dissolve the resin away from the fiber. These procedures are carried out according to ASTM standards D 3171-76 and D 792-98 [4, 5].

Tensile modulus can be calculated from the test-determined fiber volume, using fiber modulus and fraction figures available from the product vendor. This result can then be compared to the tensile modulus calculated using hydroburst data. Additionally, the amount of resin bled during cure can be determined by comparing the resin content of the towpreg as manufactured to the resulting resin content of the part. Void content results are useful in providing insight about whether the winding, curing, and bagging steps are introducing or trapping volatiles within the part.

While fiber digestion quantifies the global fiber volume and other global parameters, photomicrographs shed light on the distribution of fibers and resin within the composite matrix. Many features including fiber density gradients, resin veins, misaligned fibers and fiber nesting patterns can be ascertained, as demonstrated in Figs. 17 and 18. The oval shaped, white structures in Fig. 17 indicate misaligned fibers that can reduce mechanical and electrical performance. These misaligned fibers, at least in this region pictured, are oriented in and out of the paper. In an ideal arrangement white, straight lines would dominate the area with a small amount of dark region, which represents the resin matrix.

In Fig. 18, the white round structures are individual fibers (filaments). This photomicrograph shows evidence of uneven fiber distribution with the associated resin rich regions. Also shown is a region of hexagonal geometry, which is desirable and necessary to achieve maximum possible fiber volume.

***Post-processing of test results* -** Normally, a minimum of eight samples or coupons are tested for each test described. This test set quantity is the lower threshold for meaningful statistical numbers. In the case of viscoelastic tests this is not possible given the lengthy time frame for obtaining data and economics. Results obtained from these tests are used to calculate averages, maximums, and standard deviations. Ultimately all data will be quantified with statistical analysis following the standard MIL-HDBK-17 specifications, which allows a confidence level to be determined for the data based on the spread of the results and the number of samples, commonly referred to as A-basis and B-basis allowables.

Summary

Composites are attractive materials for pulsed power rotating machinery; however, their anisotropic nature of performance (and, in some cases, limited availability of thermomechanical data) necessitates testing to determine performance and establish design allowables. UT-CEM conducts tests that provide both fiber and resin dominated material properties that are then post-processed to establish allowable values for use in machine design.

Acknowledgement

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References

1. Test Method D5450/D5450M-93 (2000), "Standard Test Method for Transverse Tensile Properties of Hoop Wound Polymer Matrix Composite Cylinders," American Society for Testing and Materials.
2. Test Method D3039/D3039M-00, "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials," American Society for Testing and Materials.
3. Test Method D3846-94, "Standard Test Method for In-Plane Shear Strength of Reinforced Plastics," American Society for Testing and Materials.
4. Test Method D3171-99, "Standard Test Method for Constituent Content of Composite Materials," American Society for Testing and Materials," American Society for Testing and Materials.
5. Test Method D792-00, "Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement," American Society for Testing and Materials.

TABLES

Table 1. Typical results summary for a set of hydroburst test rings

Banding #	1	2	3	4	6	7	8	9	Strain Gauge Info	
Width (min)	0.484	0.485	0.484	0.485	0.485	0.485	0.485	0.48	Type:	Hoop
Width (max)	0.487	0.486	0.486	0.486	0.487	0.487	0.486	0.484	Gauge Factor:	2.06
Width (avg)	0.4855	0.485	0.4850	0.4855	0.486	0.486	0.4855	0.4820	Type:	Axial
Thickness (min)	0.096	0.097	0.097	0.096	0.097	0.097	0.095	0.0.97	Gage Factor:	2.045
Thickness (max)	0.098	0.098	0.098	0.097	0.104	0.098	0.097	0.098	Winding Summary	
Thickness (avg)	0.097	0.0975	0.0975	0.0965	0.1005	0.0975	0.0960	0.0975	Material: T1000G/977-2	
OD	20.297	20.298	20.294	20.299	20.296	20.294	20.294	20.296	Spool #1	
ID	20.103	20.103	20.099	20.106	20.095	20.099	20.102	20.101	Spool #2	
									Lot #	
									Resin %	
									Tow Tension	

Pressure (psi)	1	2	3	4	6	7	8	9	Max (psi x 10^3)	Avg (psi x 10^3)	Stan Dev (psi)
Maximum pressure transducer reading	4,320	4,400	4,080	4,370	4,360	4,290	4,270	4,270	4,400	4,290	99.5
Maximum manual gauge reading	4,370	4,300	4,350	4,700	4,375	4,150	4,500	4,300	4,700	4,380	162
Stress (psi x 10^3) max hoop laminate	455	461	427	464	443	450	455	448	464	450	11,600
Strain (x 10^6), maximum hoop	17,700	17,700	16,600	17,700	17,700	17,500	17,700	17,300	17,700	17,500	401

Table 2. Test results from transverse electrical conductivity tests (two samples from the same hydroburst ring)

Sample #	Painted?	Pressure (psi)	Width (in.)	Length (in.)	Thickness (in.)	Volts (V)	Current (A)	Conductivity
1	Y	5,000	1.975	0.48	0.12	118.6	193.6	130.160689
1	Y	5,000	1.975	0.48	0.12	118.8	194.2	130.3442747
1	Y	5,000	1.975	0.48	0.12	118.7	193.9	130.2525591
1	Y	**2,500**	1.975	0.48	0.12	118.72	191.36	128.5246557
1	Y	**1,250**	1.975	0.48	0.12	119.04	189.44	126.8930808
2	Y	5,000	1.95	0.48	0.12	119.3	180.8	122.3910458
2	Y	5,000	1.95	0.48	0.12	119.4	181.4	122.6943656
2	Y	5,000	1.95	0.48	0.12	119.4	180.8	122.2885408
2	**N**	5,000	1.95	0.48	0.12	120	170.88	115.0010095
2	**N**	5,000	1.95	0.48	0.12	120	170.56	114.7856518

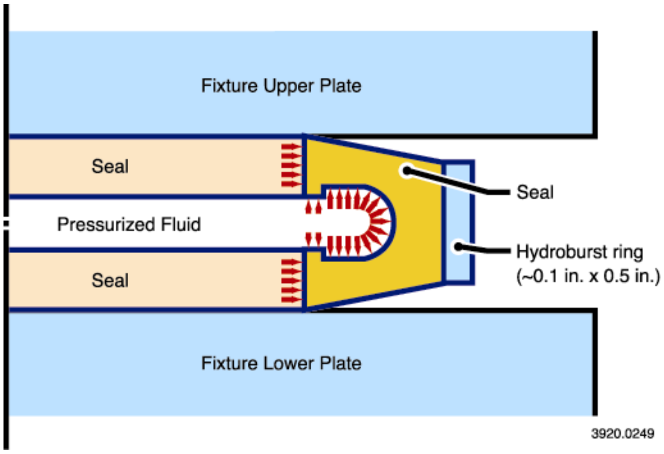

Figure 1. Cross-section of hydroburst fixture

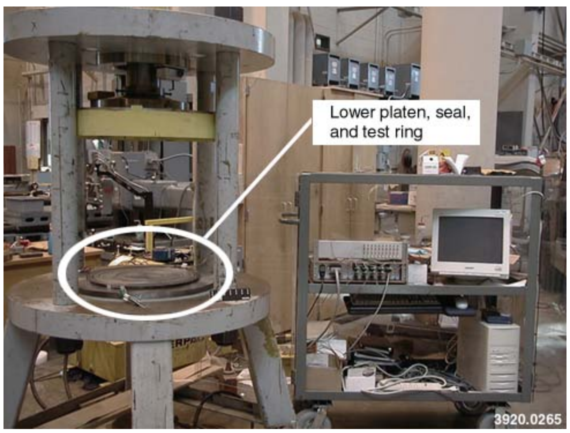

Figure 2. Hydroburst fixture in press station

Figure 3. Instrumented hydroburst ring

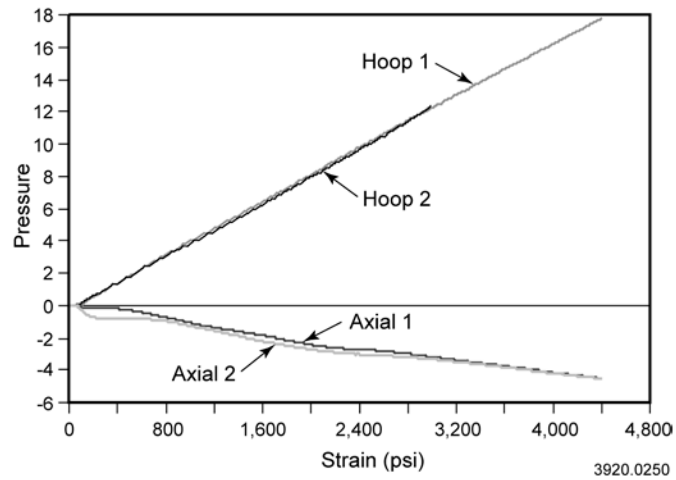

Figure 4. Typical strain vs. pressure chart from one hydroburst ring test*

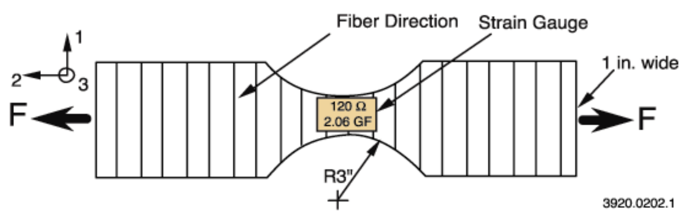

Figure 5. Transverse tensile test specimen

Figure 6. Hydroburst transverse tensile test specimen in tensile tester with environmental chamber in open position

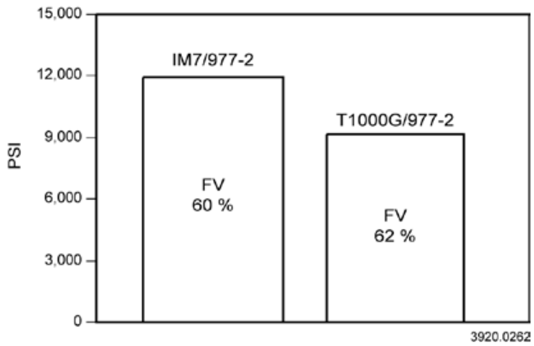

Figure 7. Failure strength chart for two sets of flat coupon specimens

Figure 8. Double-notch shear strength test coupon

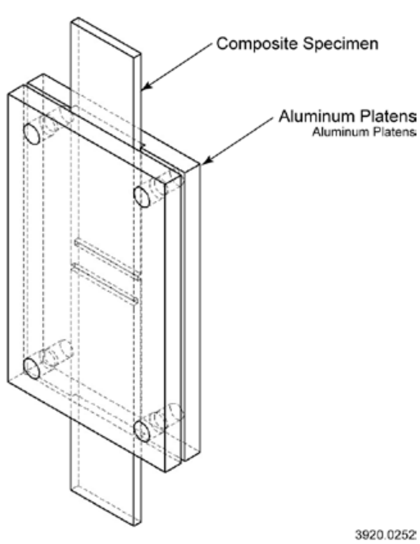

Figure 9. Schematic of test coupon sandwiched between restraining guide plates

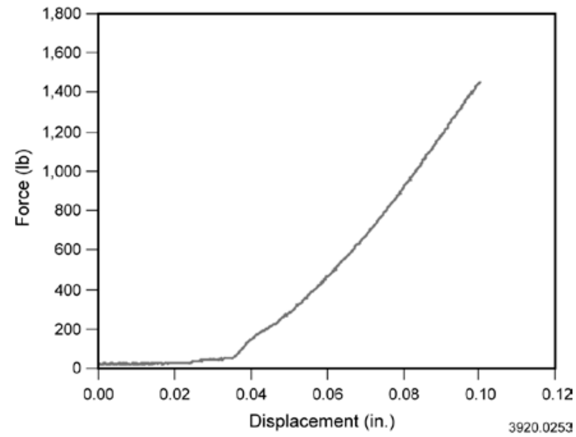

Figure 10. Typical data from a double-notch shear strength test

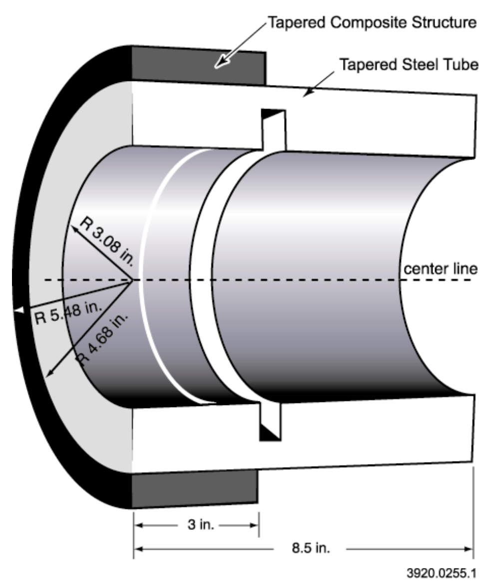

Figure 11. Fixture for assessing viscoelastic behavior of circular composite structures

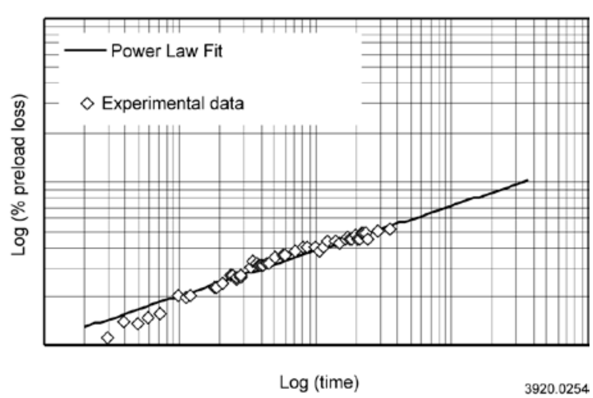

Figure 12. Typical log plot of the viscoelastic effects driving radial preload loss at a composite interface

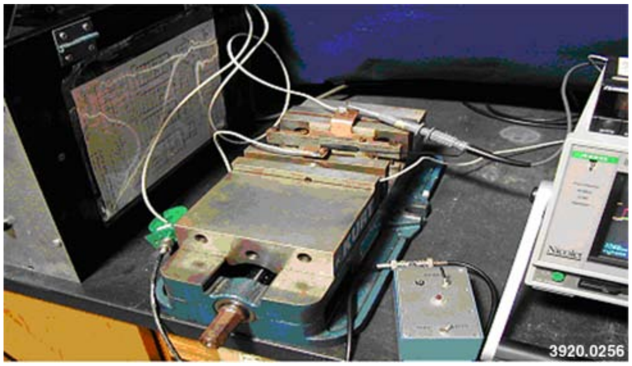

Figure 13. Transverse electrical conductivity fixture

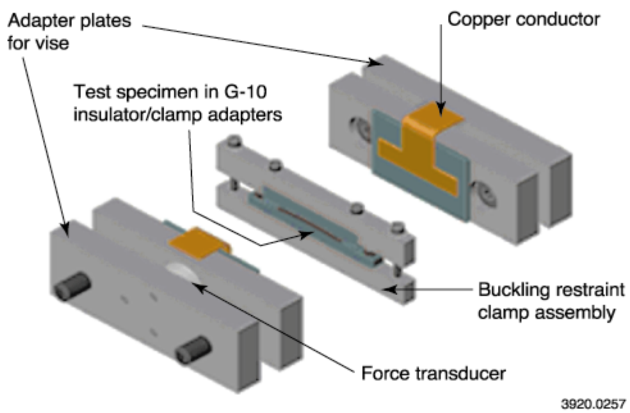

Figure 14. Exploded view of transverse electrical conductivity fixture (machinist's vise not depicted)

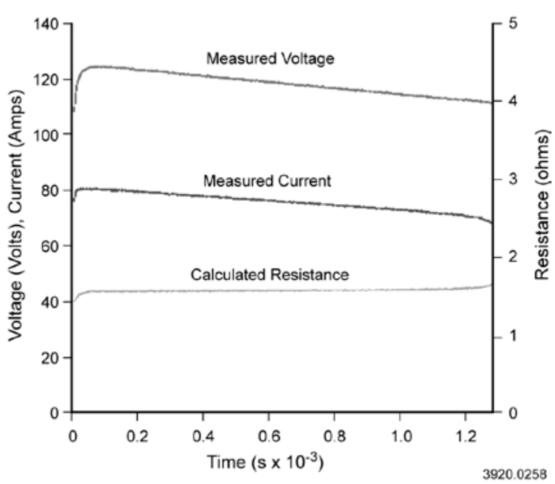

Figure 15. Typical test trace for transverse electrical conductivity

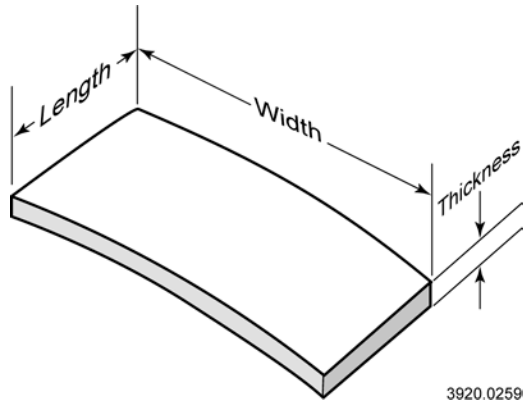

Figure 16. Key for dimensions of transverse electrical conductivity test sample

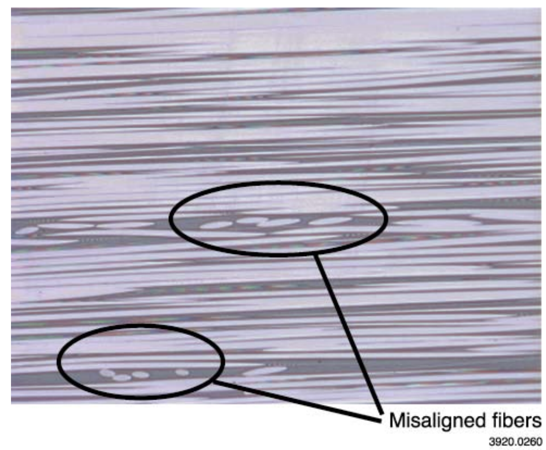

Figure 17. Side view photomicrograph of misaligned fibers (ovals)

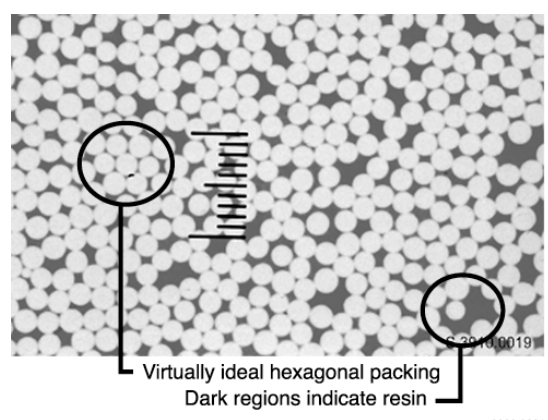

Figure 18. End view (hoop face) photomicrograph showing fiber distribution